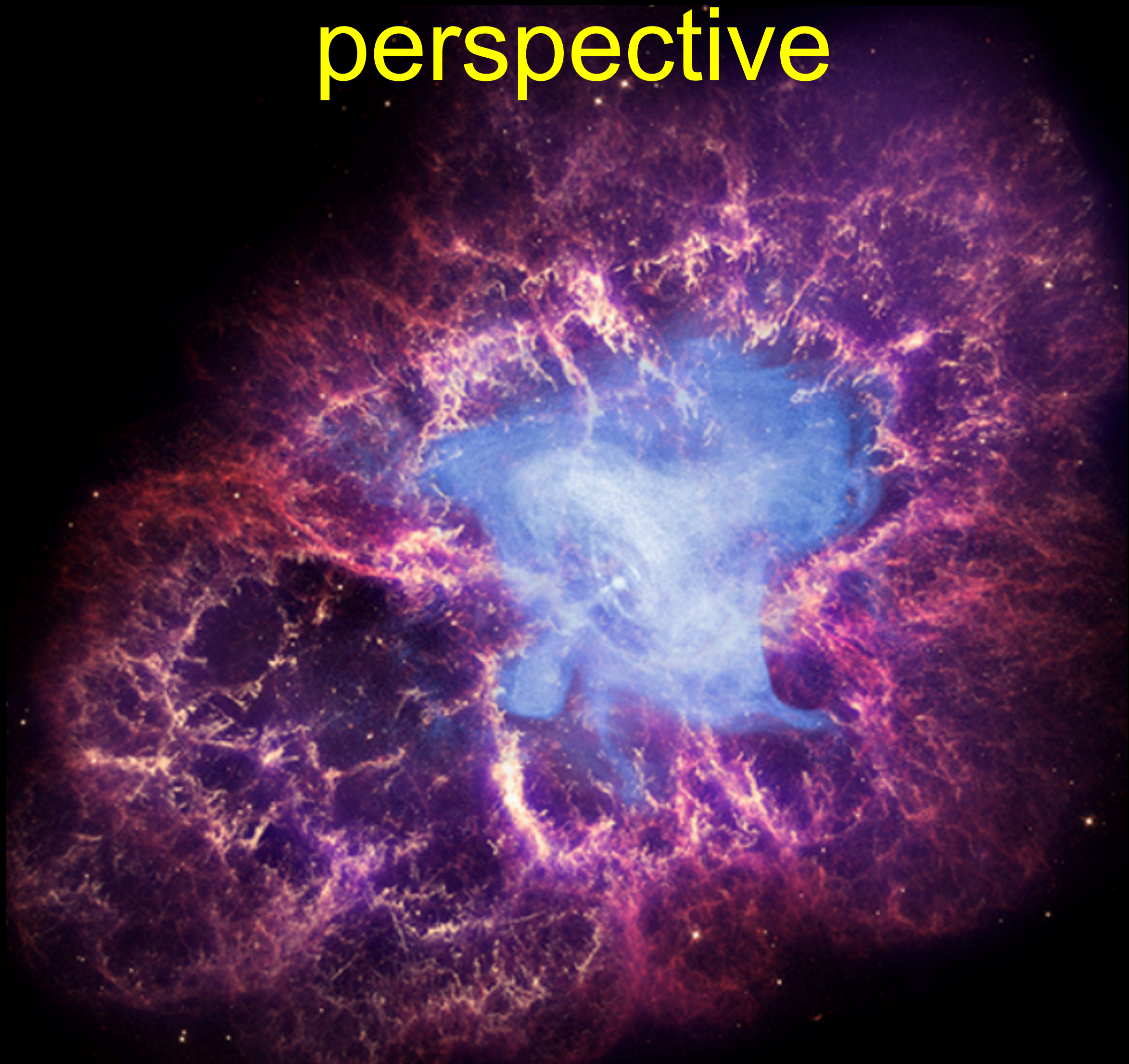
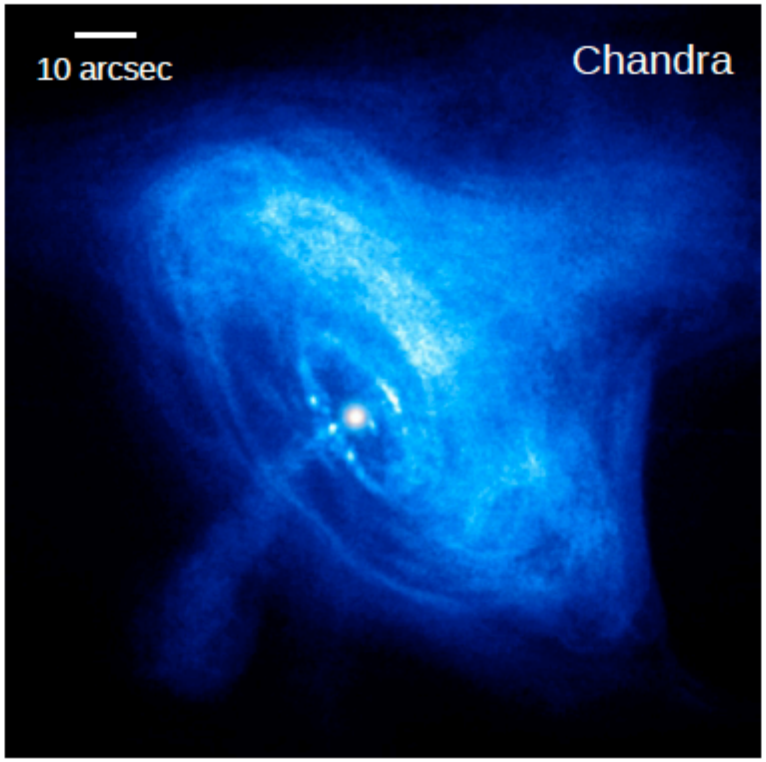
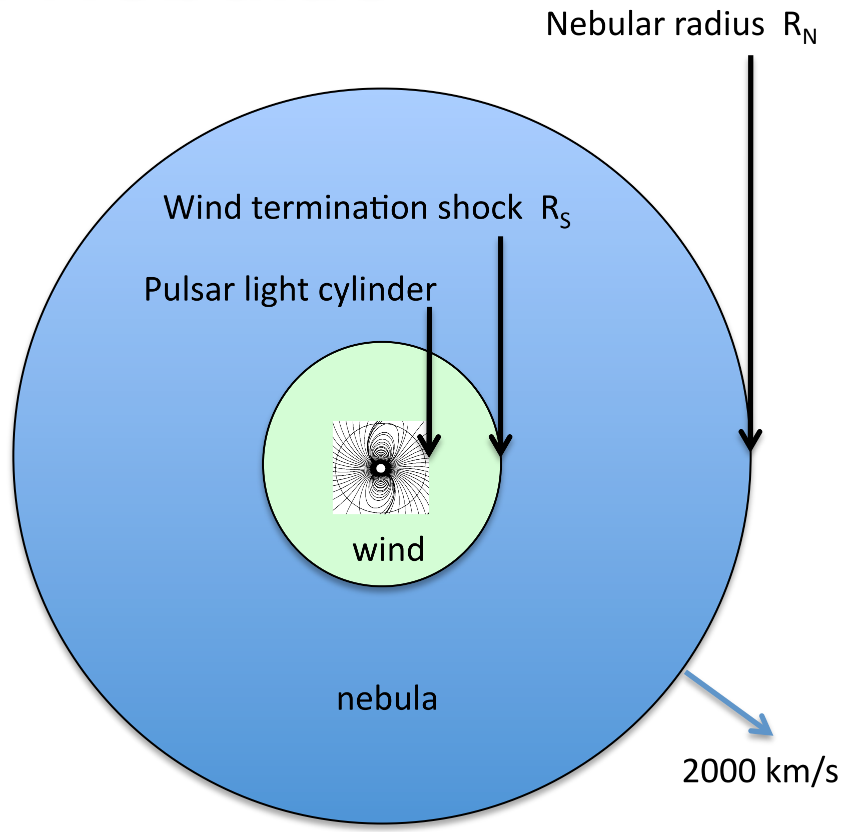
The Crab Nebula: a theorist's perspective



Alice K. Harding (NASA/GSFC)

Pulsar Wind Nebulae





Crab nebula

- Remnant from 1054 AD supernova at 2 kpc
- Young energetic pulsar powers pulsar wind nebula (Pacini 1967)
- Standard reference in X-rays and VHE gamma rays

Termination shock radius

Wind pressure = Nebular pressure

$$\frac{\dot{E}_{sd}}{4\pi c R_S^2} \approx \frac{\dot{E}_{sd}\tau}{\frac{4}{3}\pi R_N^3} \Rightarrow R_S \approx 3\times 10^{17}\,cm$$

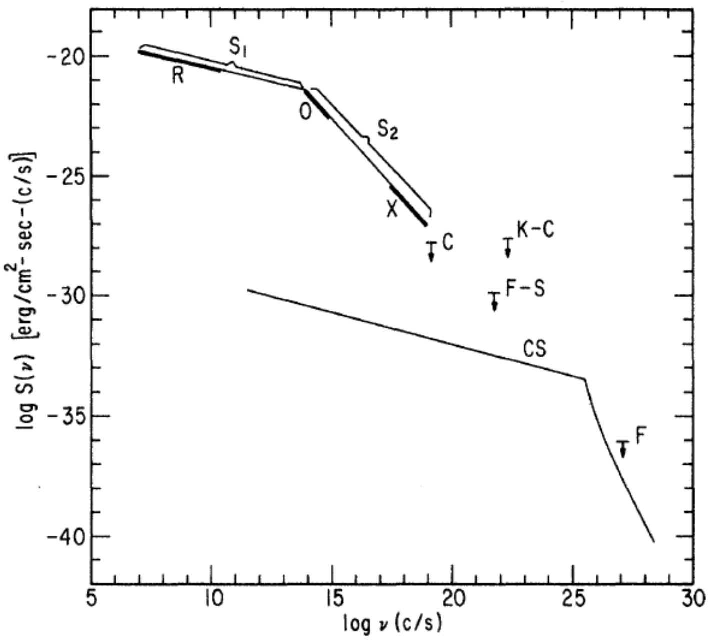
Rees & Gunn (1974)

First Synchrotron-self Compton models of the Crab Nebula

Gould 1965 – uniform B, Thomson σ_C

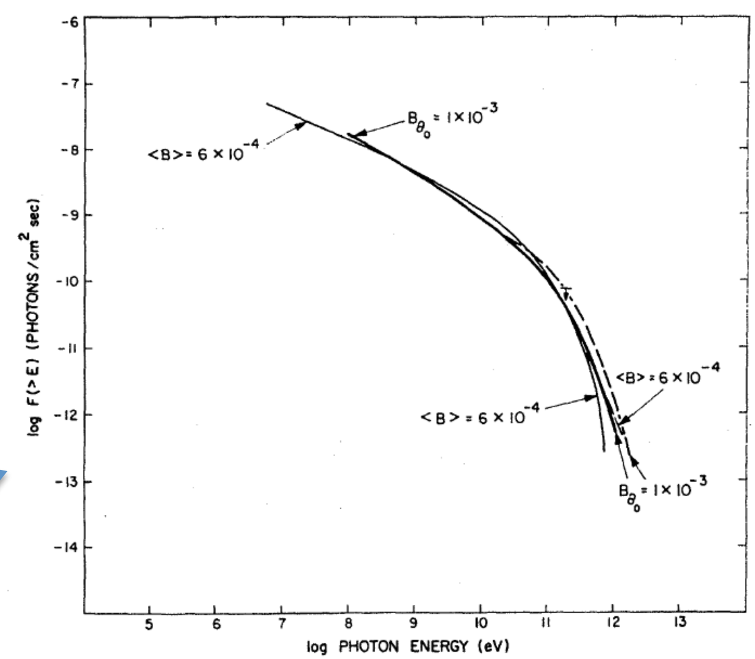
$$J(\varepsilon) = \frac{1}{4\pi d^2} \int dV \int d\gamma \; n_e(\gamma) \int d\nu \; n_{ph}(\nu) \; \sigma_C(\gamma,\nu)$$

- Volume integral – assumed spherical
- Electron spectrum – derived from observed synchrotron spectrum
- Soft photon spectrum - synchrotron



Rieke & Weekes 1969 – KN (delta-function)

Grindlay & Hoffman 1971
- KN cross section of Jones 1968
- IC spectrum can be used to constrain nebular B field



Better Crab Nebula models

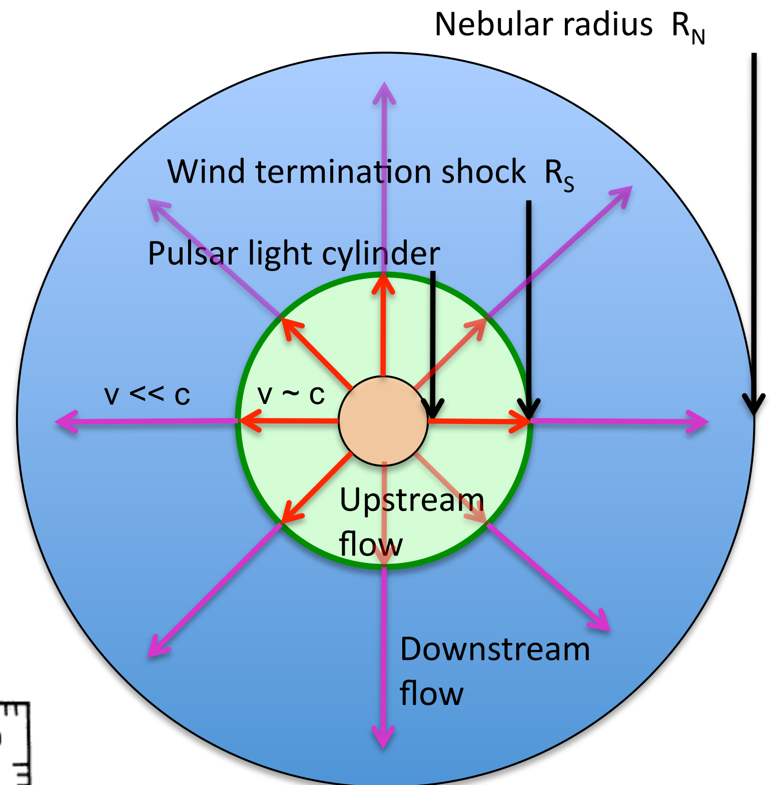
MHD model of pulsar wind (Kennel & Coroniti 1984)

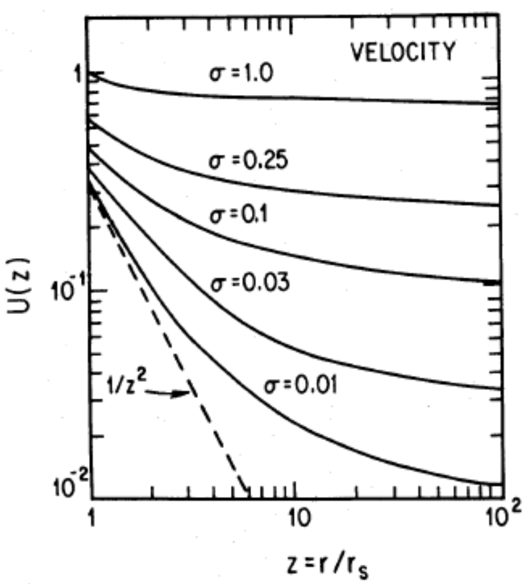
$$\sigma \equiv \frac{\text{Magnetic energy density}}{\text{Particle energy density}} = \frac{B_1^2}{4\pi n_1 u_1 \gamma_1 mc^2} << 1$$

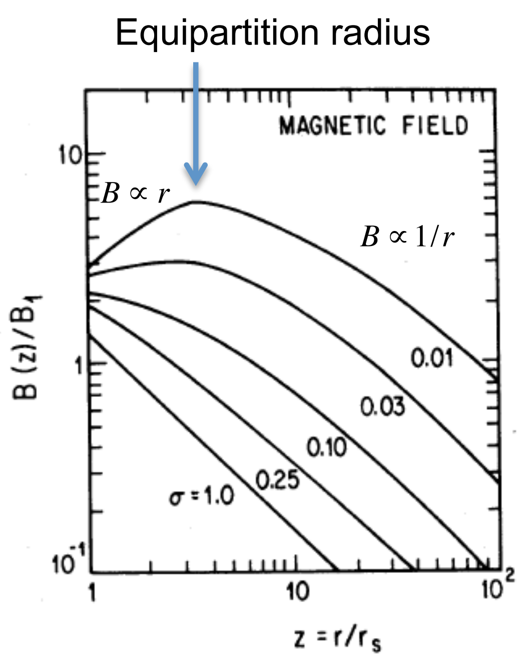
(Rees & Gunn 1974)

For the Crab nebula, $\sigma \sim 0.003$

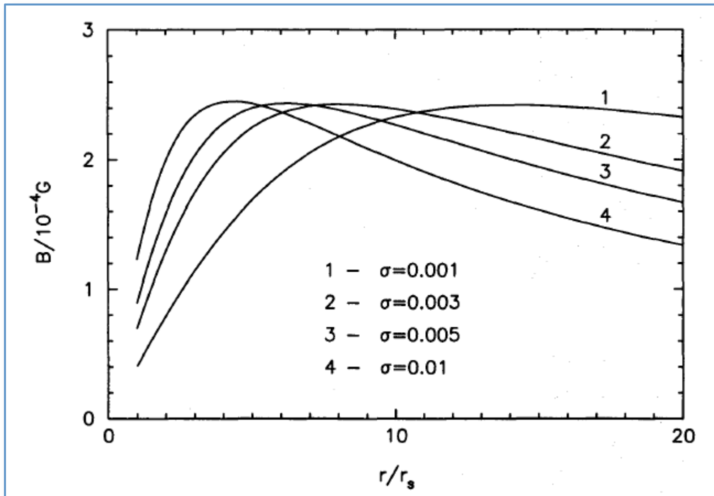
needed to decrease wind velocity from c to 2000 km/s







“Second-generation” SSC models



DeJager & Harding 1992 –

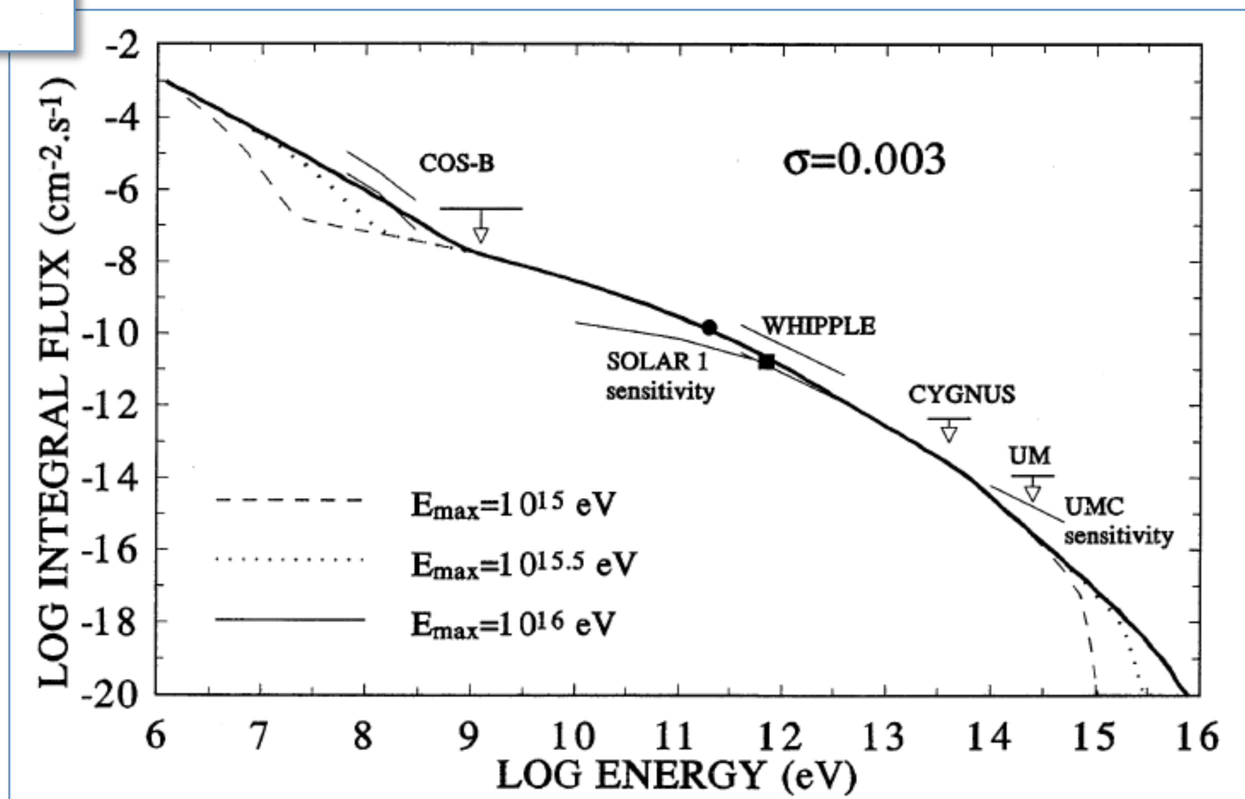
- adopted Kennel & Coroniti solution for B(r) and small σ
- spatial dependence of synchrotron, IC, electrons and photon density

- COS-B sees end of SR spectrum ~ 100 MeV

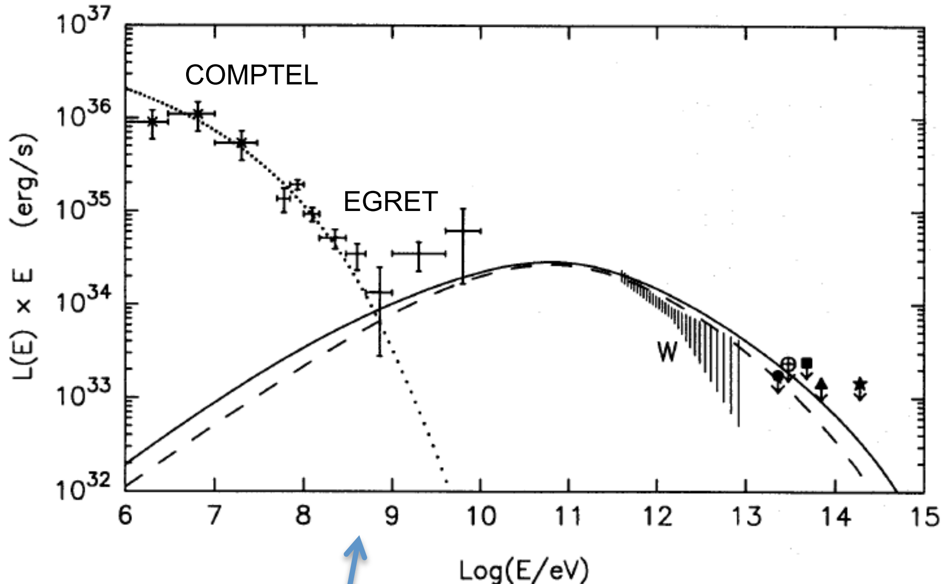
- E_{max} = 10^{16} eV is near V_{open} ~ 3 x 10^{16} eV acceleration maximum

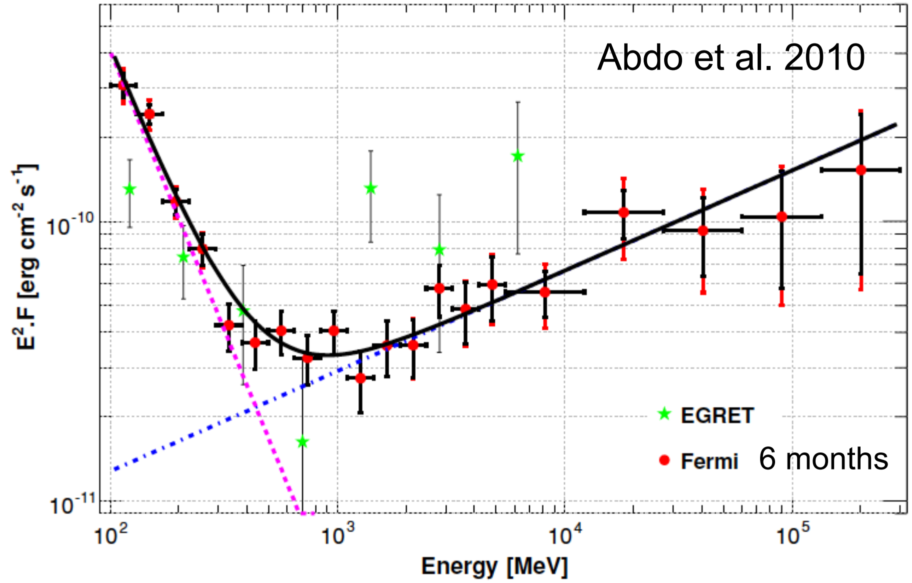
- Pair multiplicity ~ 10^5-10^6 >> theory

- Upper end of SR spectrum could be variable



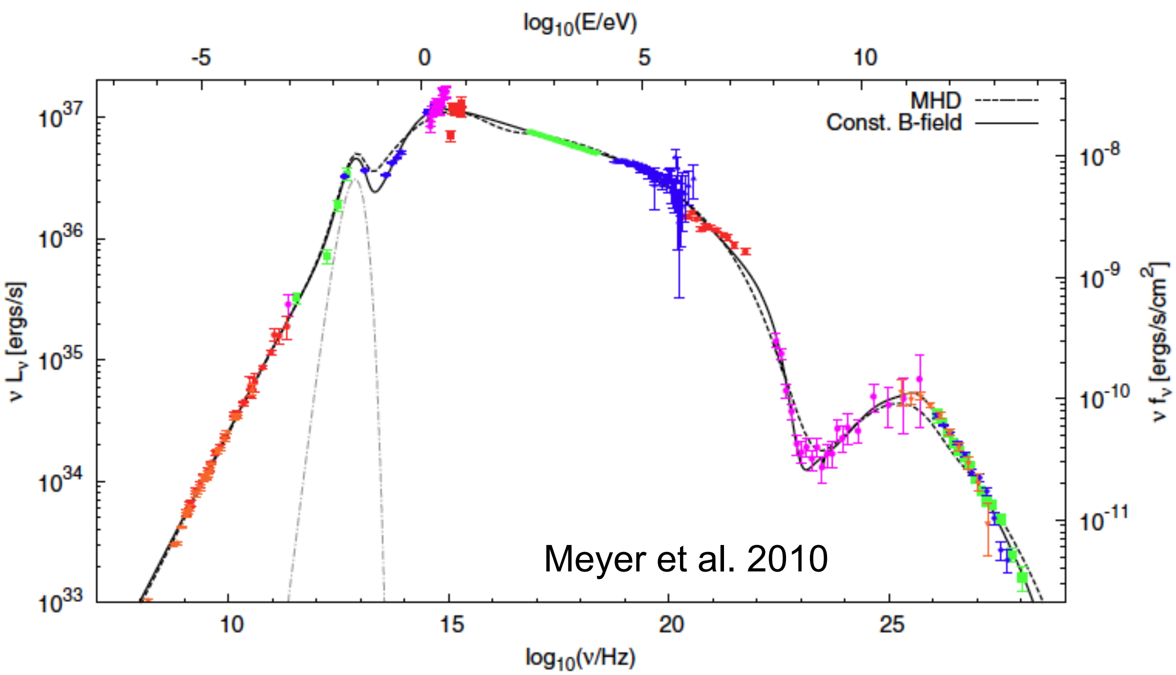
“Second-generation” SSC models





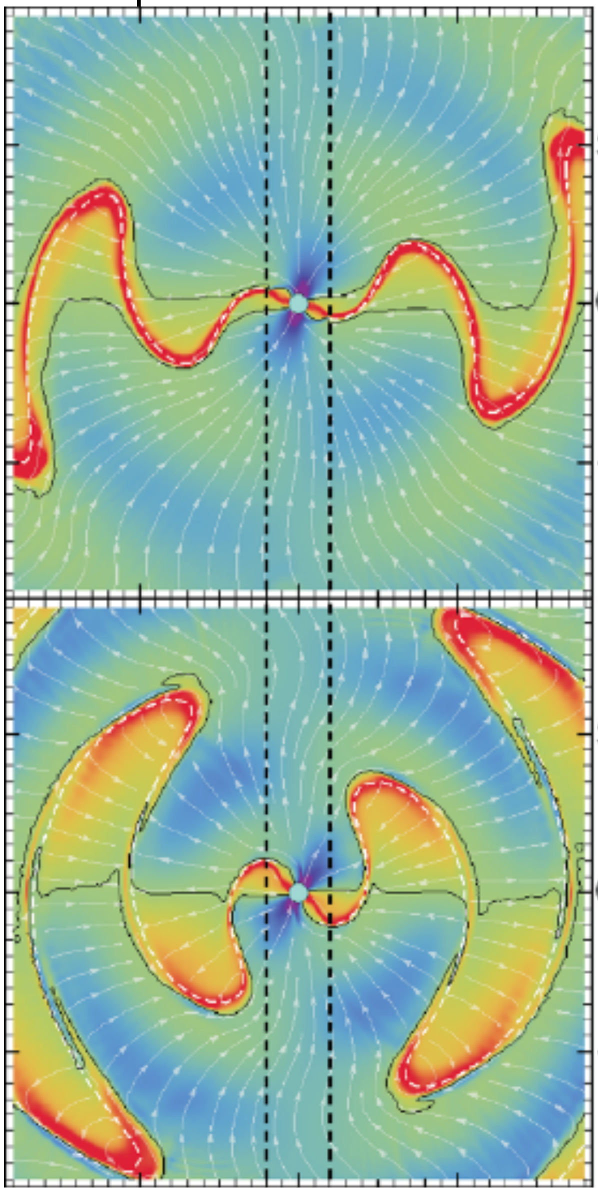
Atoyan & Aharonian 1996

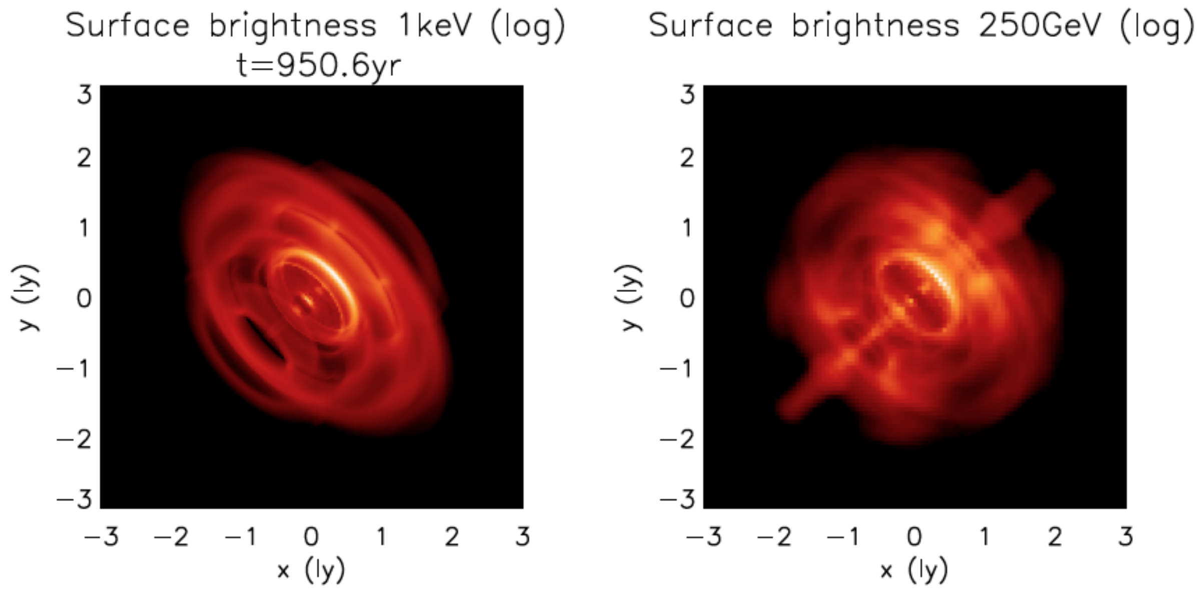
- Scattering of CMB and dust contributes ~10% to IC spectrum
- e-+ bremmstrahlung component?
- Two populations of electrons



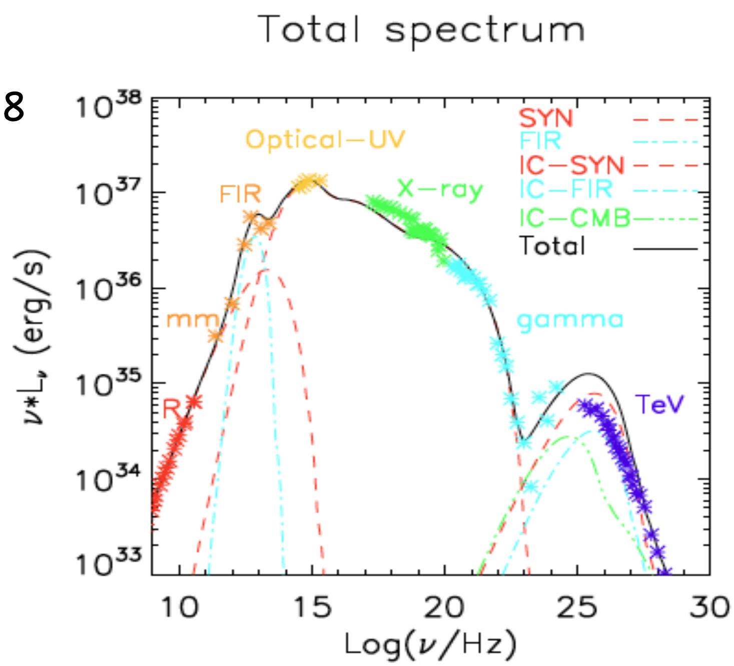
MHD simulations

Kalapothrakos et al. 2012





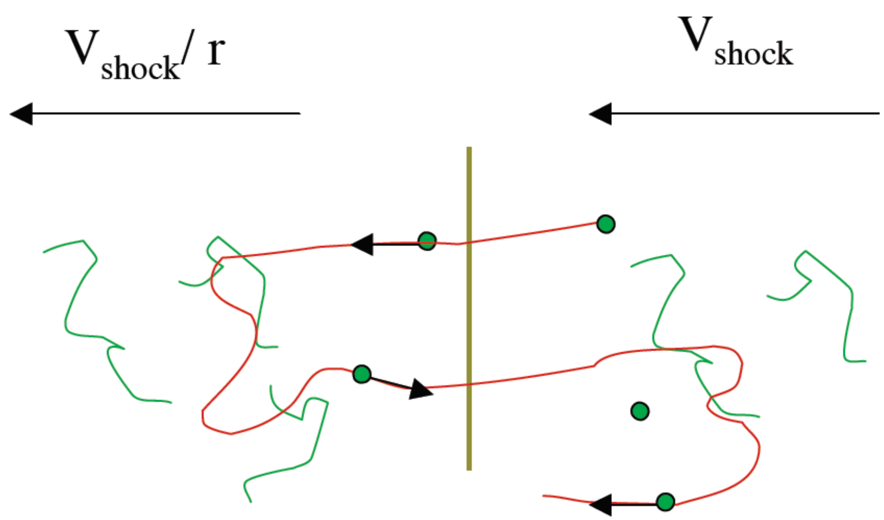
Volpi et al. 2008



Traditional acceleration models

- Diffusive acceleration (1st order Fermi) at termination shock (Fermi 1949, Blandford & Ostriker 1978, Eichler 1979)
  - Problem: Crab TS is relativistic and has B nearly perpendicular to flow

  → *superluminal*



- Resonant absorption of ion-cyclotron waves (Hoshino, Arons, Gallant & Langdon 1992)
  - Problem: requires most of spin-down energy in ions upstream of shock

Limitations of traditional models

- No diffusive acceleration at superluminal shocks – not enough turbulence to scatter particles upstream (Sironi & Spitkovsky 2009)

- At $r \sim R_{LC}$: $\sigma \sim 10^4$
  (PULSAR AND PULSAR WIND THEORIES)

  At R_S: $\sigma \ll 1$(!?!)
  (PWN THEORY AND OBSERVATIONS)

  → "σ PROBLEM"

Where does energy get transferred from fields to particles??

- Maximum SR energy from acceleration (E < B) limited by synchrotron losses

(Guilbert et al. 1983, deJager et al. 1996):

$$\dot{\gamma}_{syn}(\gamma_{\max}) = \dot{\gamma}_{acc}(\gamma_{\max})$$

$$\gamma_{\max} \propto B^{-1/2}$$

$$E_{syn}^{\max} = \frac{3}{2}\gamma^2 B \approx \frac{9}{4}\frac{mc^2}{\alpha} \cong \boxed{160\,MeV}$$

Reconnection?

- Reconnection in striped wind (Coroniti 1990)?

  Could solve three problems at once:

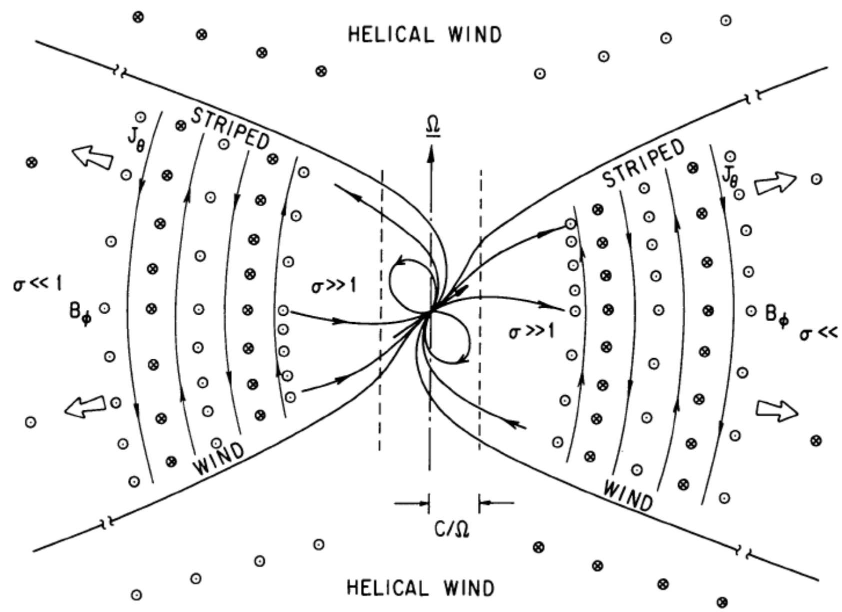
  1. Decrease σ by transferring energy to particles

  2. enable acceleration at TS

  3. E > B in reconnection layer

  → can exceed E_{syn}^{max} limit

  (Uzdenzky et al. 2011)



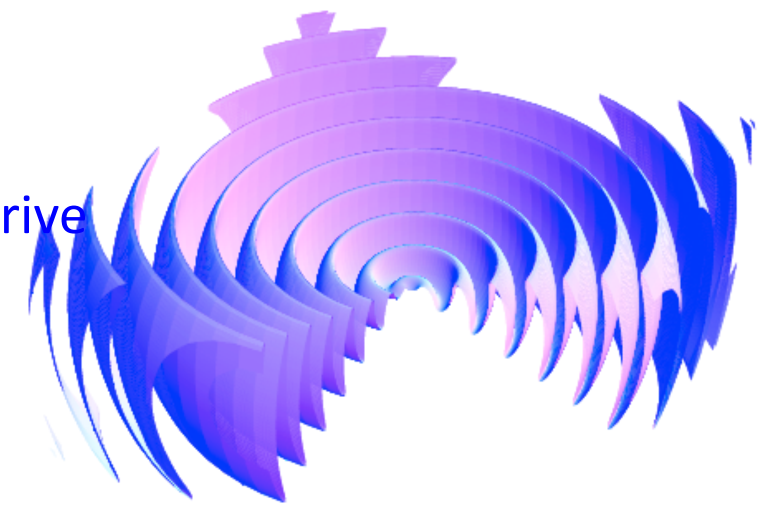
- But reconnection is not fast enough

  - wind Γ increases (Lyubarski & Kirk 2001)

- But compression of stripes near shock will drive faster reconnection –

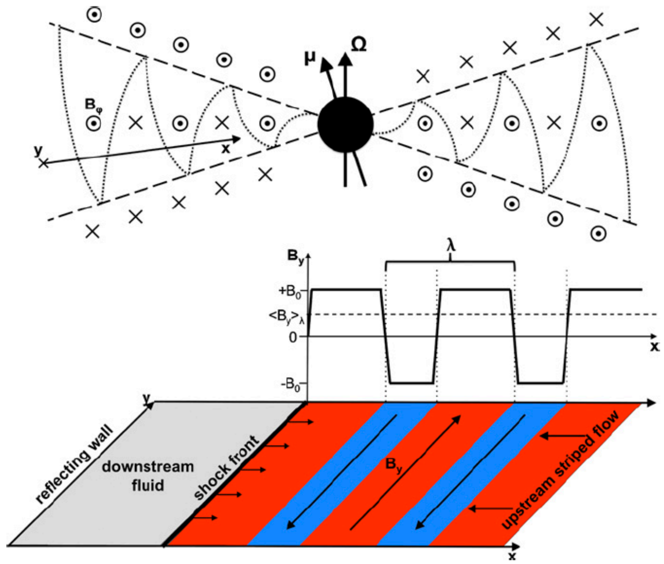
  "shock-driven reconnection"

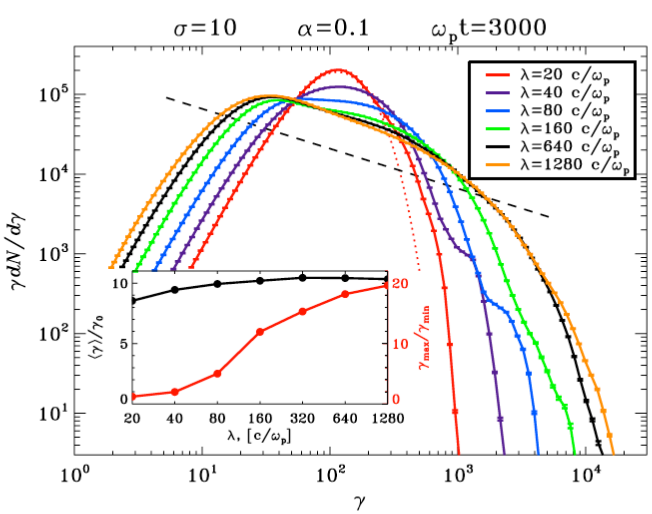
  (Lyubarski 2003, Lyubarski & Petri 2007)



Shock-driven reconnection

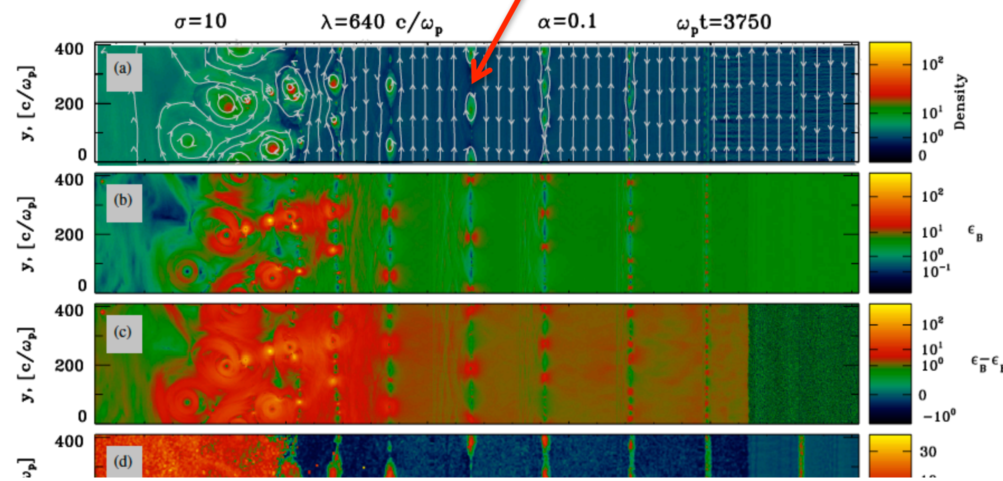
Sironi & Spitkovsky 2011





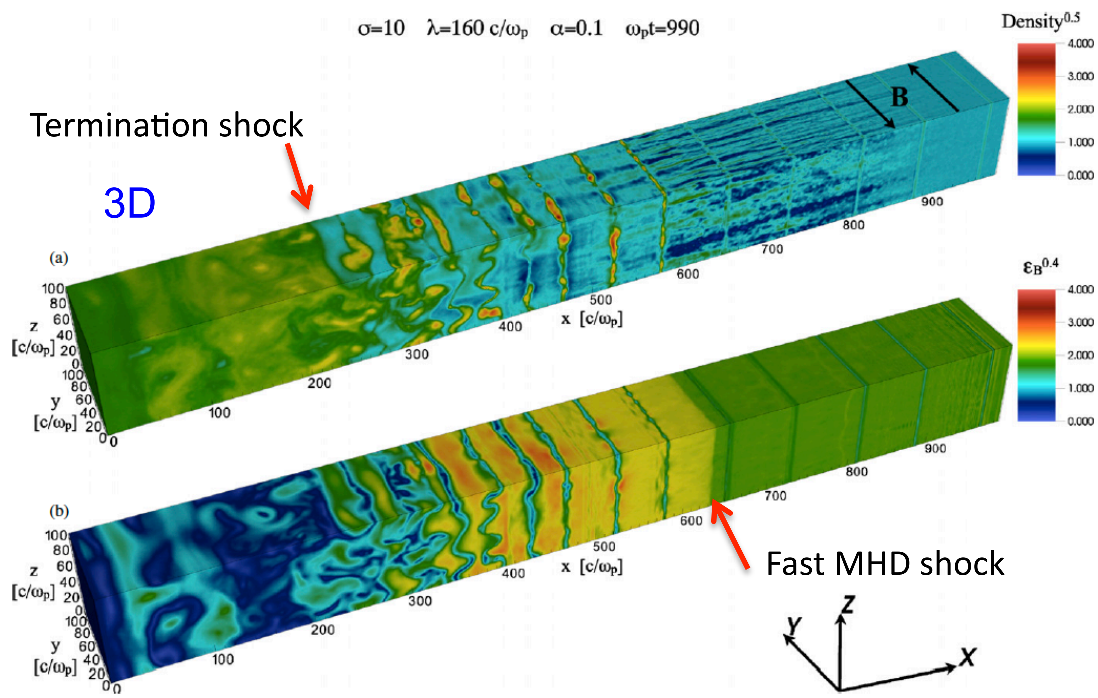
2D

Particles accelerated at X-points where E > B



Termination shock

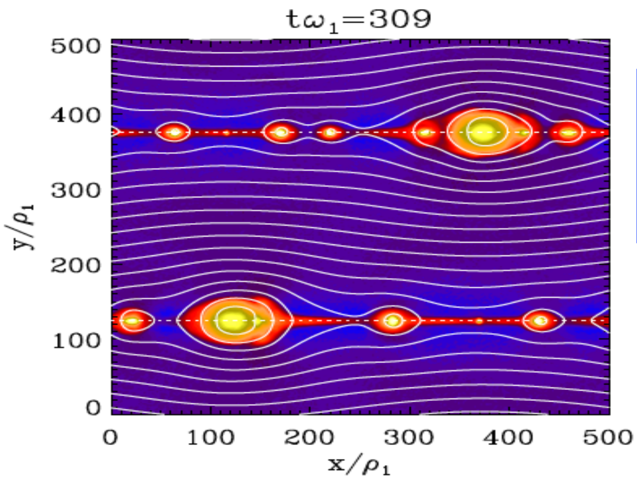
3D



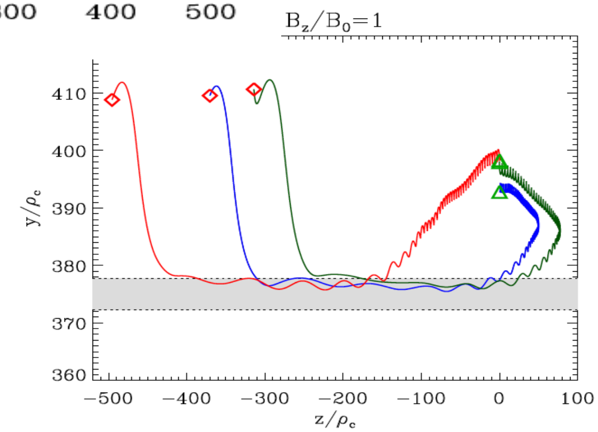
Fast MHD shock

Crab flares: reconnection in pair plasma

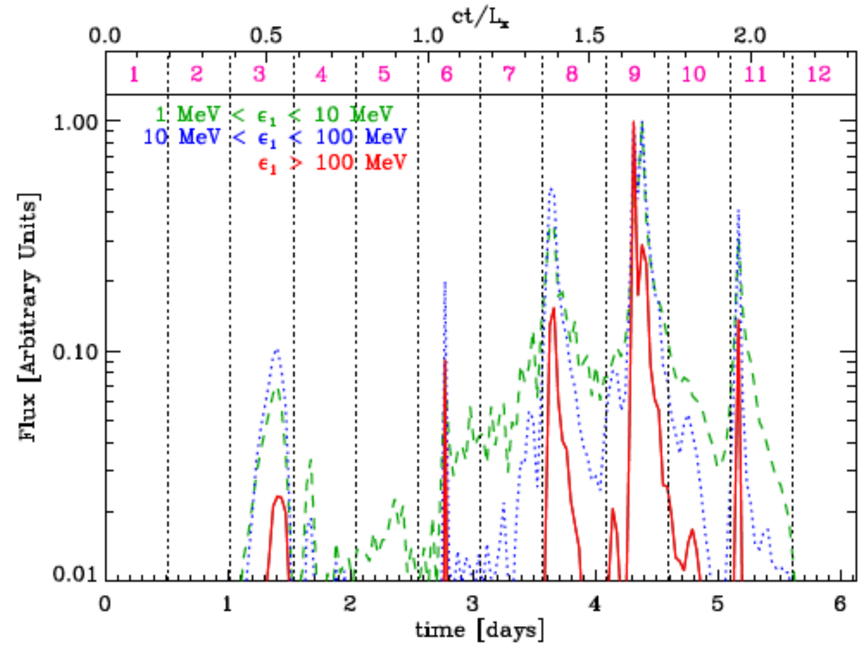
Cerutti, Uzdensky & Begelman 2012
Cerutti et al. 2013

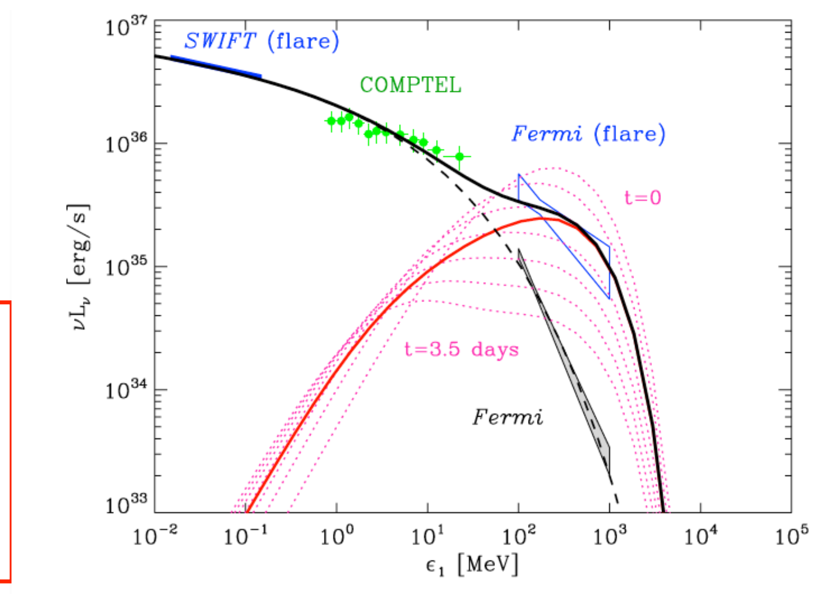


E > B in reconnection layer



Particles are focused toward reconnection layer

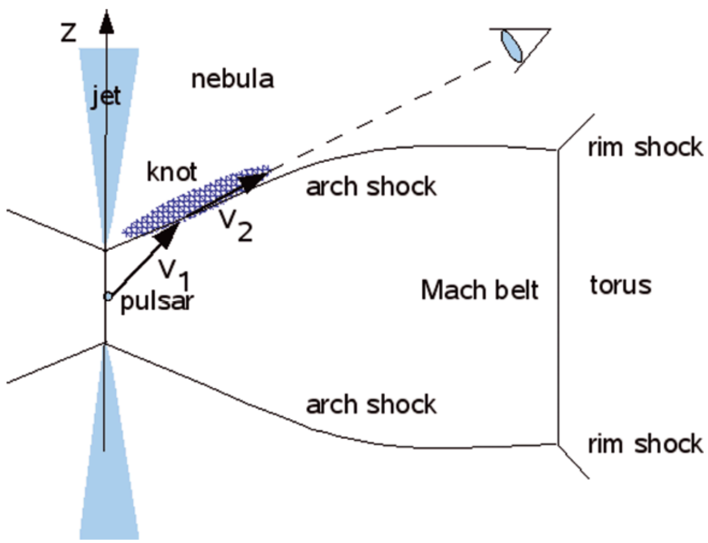


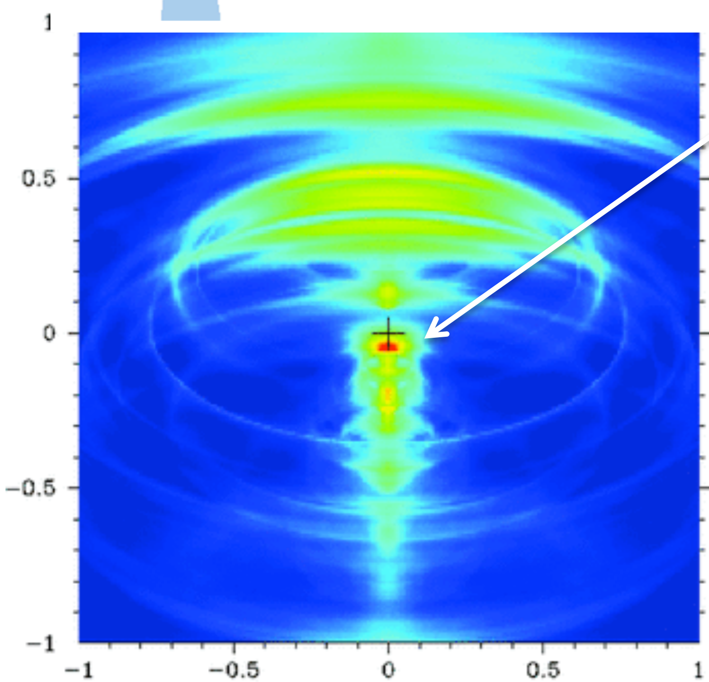


- Radiation above classical limit in RL
- Flare spectrum from mono-energetic particles with $\gamma \sim 2 \times 10^9$

Crab flares: Doppler boosting

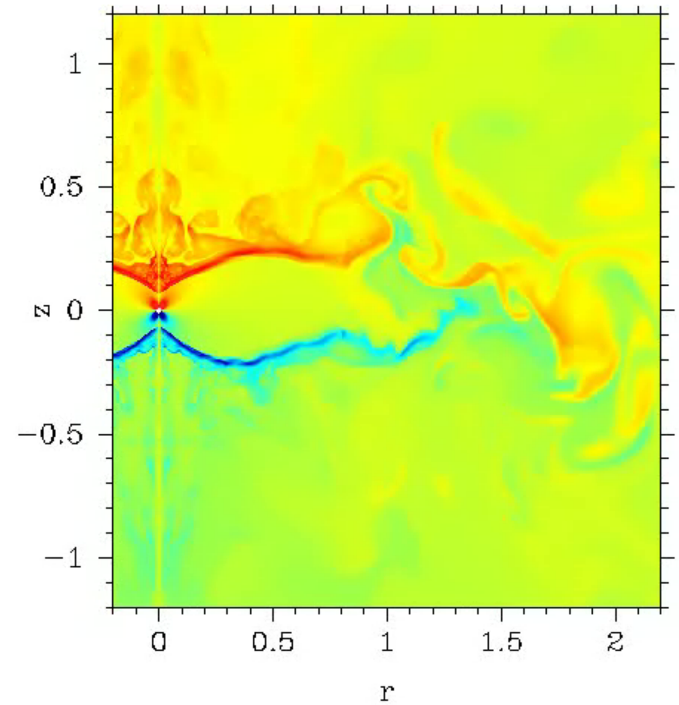
Komissarov & Lyutikov 2011





inner knot
L ~ 6 lt-days

Camus et al. 2009 – relativistic MHD sims

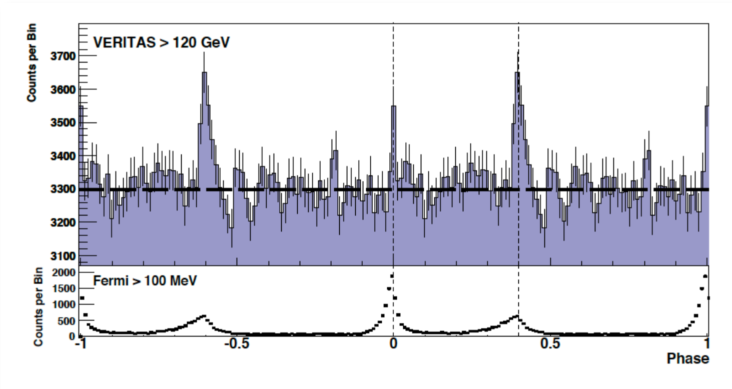


- Flares from variability of Doppler boosting of post-shock flow $\varepsilon_\gamma^{obs} = D\varepsilon_\gamma,\quad j_\gamma^{obs} = D^{2+\alpha} j_\gamma$

$$D = \frac{1}{\gamma(1-\beta\theta)}$$

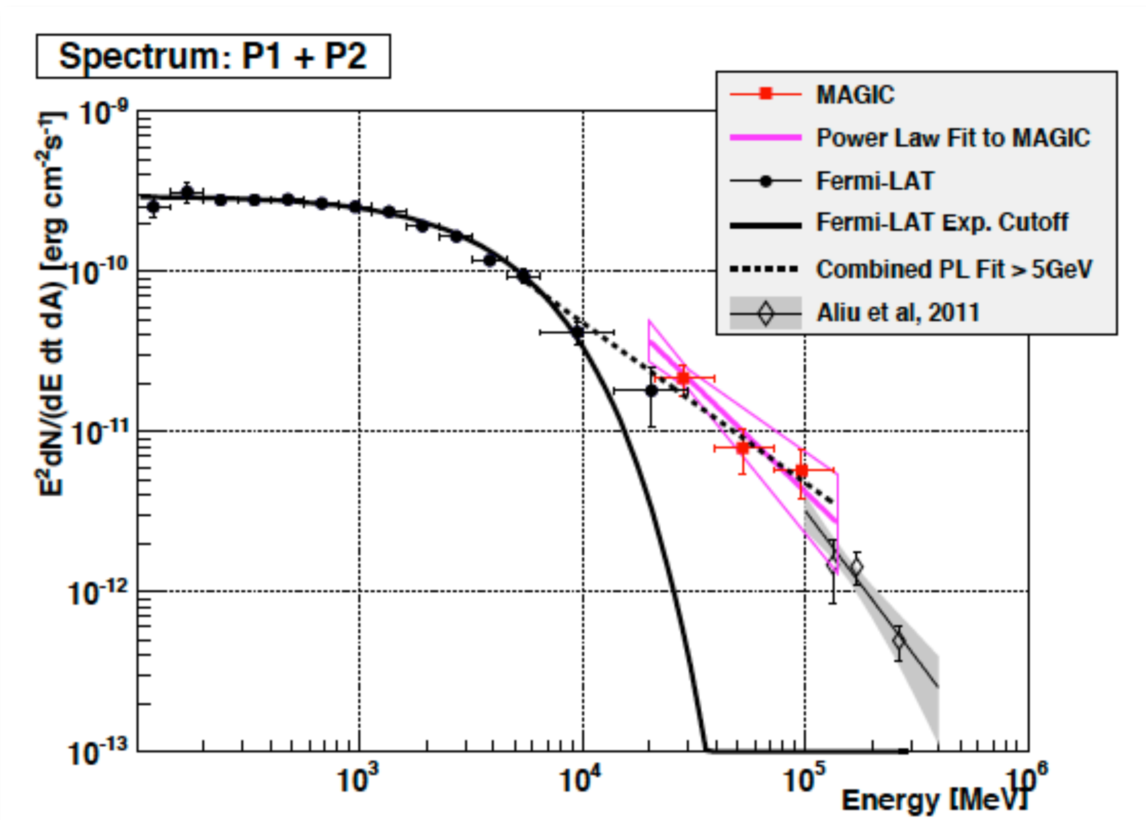
- Possibly from inner knot
- Could explain correlation between flux and cutoff energy (Lyutikov et al. 2011)

VERITAS and MAGIC detection of the Crab pulsar



Crab pulsar above 100 GeV?
No theory predicted this!

Aliu et al. 2011
Aleksic et al. 2011

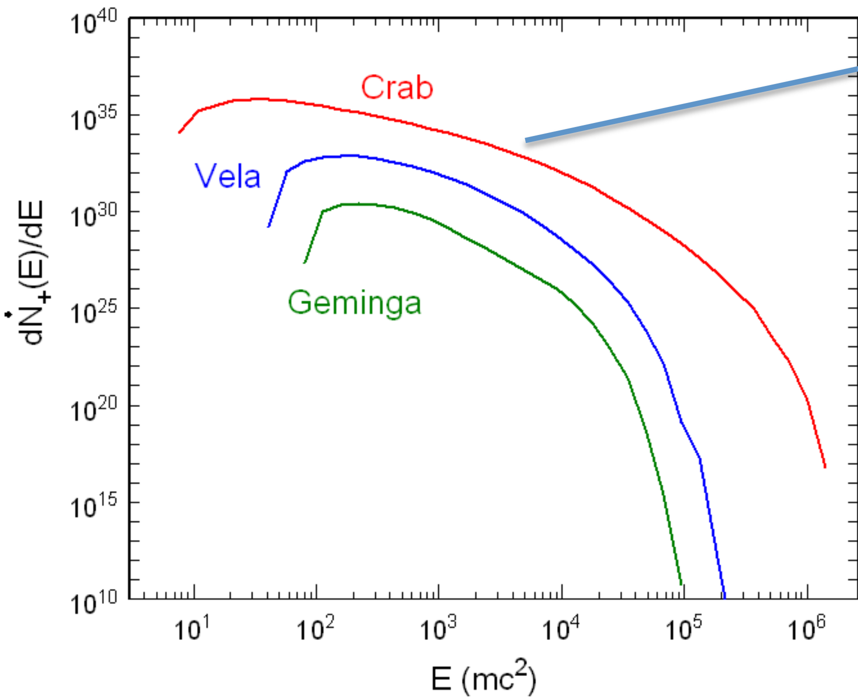


- Above 100 GeV, peaks are narrower
- Cutoff of combined spectrum is not exponential (sub-exponential?)
- Extension of Fermi spectrum or separate component (inverse Compton)?
- Is the Crab unique or do other pulsars have > 100 GeV emission as well?

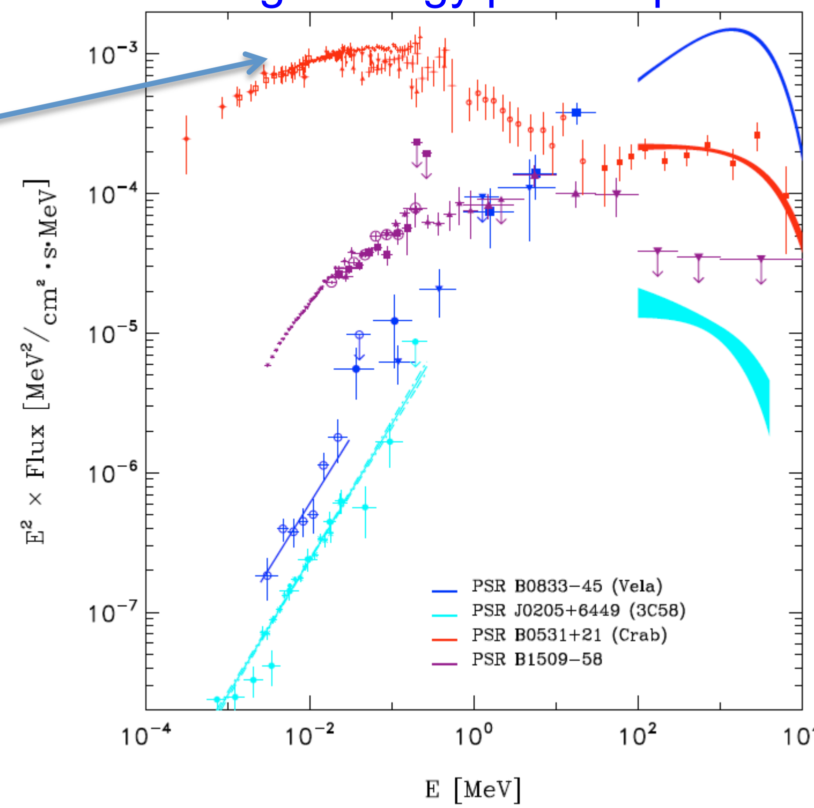
Synchrotron self-Compton emission

Essential ingredients: 1) Energetic particles
2) High synchrotron emission level

Pair cascade spectrum (polar cap)



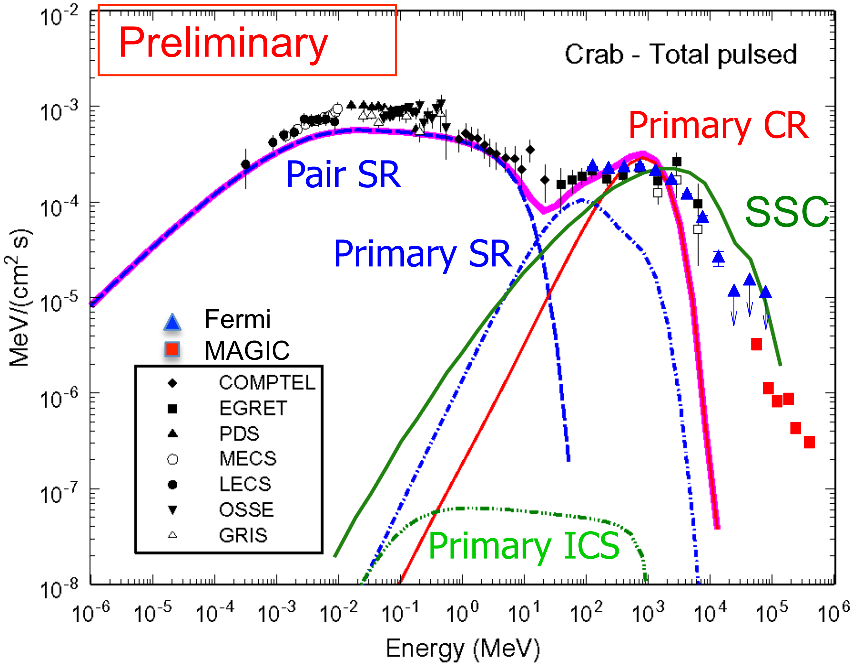
High-energy pulsar spectra



Energetic pair spectrum and high non-thermal X-rays produce high level of SSC

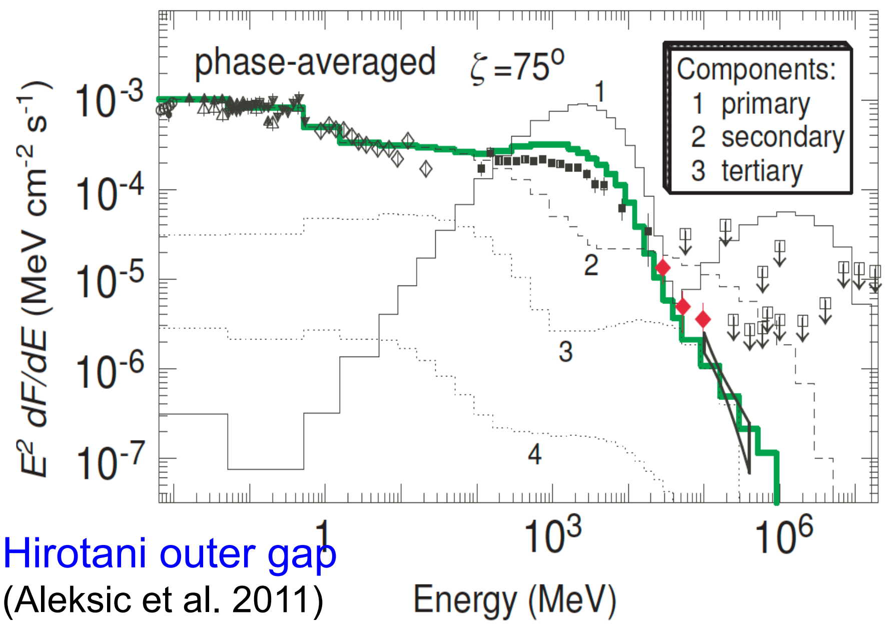
SSC emission from other young pulsars will be much lower

SSC models of Crab pulsar



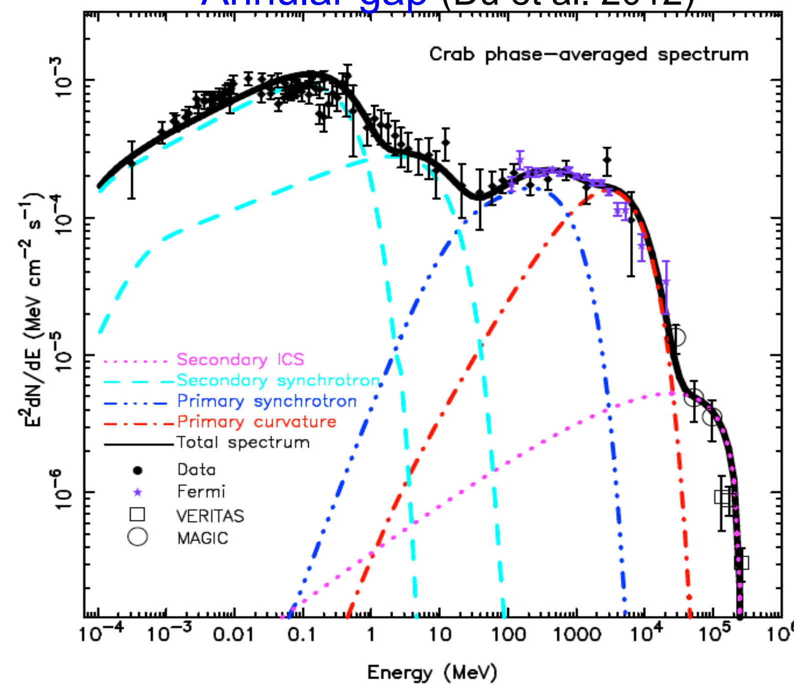
Slot gap (Harding et al. 2008, Harding 2013)

- VHE Emission is SSC from pairs
- SSC spectrum reflects pair spectrum
- Possibility of structure in HE spectrum



Hirotani outer gap (Aleksic et al. 2011)

Annular gap (Du et al. 2012)



Summary

- The Crab has been a great playground for theorists
  - IC – no evidence for bremmstrahlung or π^0 emission
  - σ problem - solved?
  - High multiplicity problem – time-dependent pair cascades?
  - Acceleration – magnetic reconnection, 1st order Fermi?
- The Crab continues to surprise and challenge us
  - Flaring of gamma-ray synchrotron emission
  - VHE pulsed emission